Internal Flow of an Electrostatically Levitated Droplet Undergoing Resonant Shape Oscillation

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ABSTRACT

Experimental evidence of internal dc flow circulation within an electrostatically levitated, 3.4 mm diameter charged water drop oscillating in shape at different amplitude is presented. The axisymmetric shape oscillations were excited using a continuously pulsed electrostatic field at the fundamental shape mode frequency (l =2) of the drop. It was found that the speed of the internal dc flow varied quadratically with respect to the oscillation amplitude without an observable minimum threshold. The implications of the observed internal flow is discussed with respect to the microgravity research facility and environment.

The behavior of shape oscillations of unbound, charged and neutral drops has been extensively studied both theoretically[1,2] and experimentally.[3,4] Acoustic/ultrasonic levitation systems[4] were among the most widely used for experiments and later, electrostatic levitators[5] also became available. Most of past levitated drop shape oscillation studies, however, placed more emphasis on the various modal excitations and their relative shapes, and only an isolated experimental observation in liquid-liquid system using an acoustic levitator has reported on the internal motion of the drop[4]. It has been very difficult to achieve a quiescently levitated droplet, free of external perturbations such as the uncontrollable drop rotation and internal flow. As a result, very little is known about what goes on inside the oscillating liquid drop. If internal flow due to the oscillating or vibrating body does indeed exists, it will hinder the measurement of thermophysical properties, such as the thermal diffusivity that rely on the quiescence of the internal state of the sample. In low-gravity, subtle flow mechanisms like thermocapillary driven convection or flow due to the vibration of the experimental apparatus become more significant. Vibration driven flow, however, has only been recently examined, despite the influence it may have in the fluid processes. In this letter, we report the experimental verification of the presence of flow inside a vibrating fluid body using the direct visualization of the interior of an electrostatically levitated, charged water drop driven into resonant shape oscillations.

The electrostatic droplet levitation technique used for this particular experiment was described in previous paper[5]. The drop shape and the oscillation phenomena have been studied using numerical methods[2]. For an axisymmetric and inviscid charged spherical drop in the absence of electric field and gravity, the resonant frequency ω_2 of the oscillating drop for the fundamental mode $l = 2$ was given by Rayleigh[1] as

$$\omega_2^2 = \frac{8\sigma}{\rho R_o^3}\left[1 - \frac{Q^2}{64\pi^2\sigma\,\varepsilon_o R_o^3}\right], \tag{1}$$

where Q is the surface charge on the drop, R_o is the drop radius, ρ its density, σ its surface tension, and ε_o the permittivity of the medium. A numerical expression[2,6] of ω_2, for electrostatically levitated charged drop against gravity, is also available.

A 20 μl water droplet containing tracer particles with an average size of 10 μm (Pliolite, Goodyear Chem. Co) was electrostatically levitated. The average control voltage to levitate the drop was 7.51 kV. The drop bore a charge of approximately 6.65×10^{-10} Coulomb. The initial, unperturbed shape of the levitated drop was axisymmetric and nearly spherical with the vertical to horizontal axial ratio of 1.013. A prolonged observation of the drop reported previously[5], confirmed that the surface charge on the electrostatically levitated drop does not produce observable internal flow. The chamber was equipped with a temperature and a humidity controllers to fix the temperature and the humidity near the levitated drop at 20°C and 90% RH, respectively, to reduce potential convection related to the evaporation and the buoyancy within the drop. Nevertheless, a finite but much slower background convection (~50 μm/minute) of the tracer particles still persisted; however, this motion was much slower compared to the oscillation induced flow. The experimental duration for each set of data was kept for less than 30 seconds in order to minimize the cumulative effects of the background flows.

The resting droplet was suddenly excited by imposing a shape oscillation using an electrostatic train of pulses. These pulses were triggered externally to stimulate drop shape oscillations at the fundamental ($l = 2$) frequency. Each pulse from the applied train was constructed by subtracting a controlled amount from the levitation voltage (Fig. 1). The pulse width was 4.5 msec. For a 20μl droplet, the observed resonant frequency of the drop was 44.4 Hz. This was slightly lower than the predicted value from Eq. (1) of 48.5 Hz and from more accurate numerical result[2,6] of 47.6 Hz. Strobed illumination of the oscillating drop revealed roughly oblate and prolate elliptical shapes but with sharper curvature at the top of the prolate shape (Fig. 2) where the magnitude of the electric field is higher. Examination of the drop shapes from the top over complete oscillation cycle confirmed that the shapes observed in all stages of oscillation were indeed axisymmetric. A thin light sheet generated by a He-Ne laser illuminates the drop midplane containing the symmetry axis, and the 90° scattered light from the tracer is recorded by a video camera. Three sets of video recordings were produced using a different pulse height for each set. The vertical to horizontal axial ratio (Av $=$ V / H) when the drop is at the extreme prolate shape is taken as a reference point to indicate the degree of oscillation amplitude. The essential feature of the observed internal flow field is a gradual particle drifting from the top and the bottom region of the drop towards the center, a sideway motion to the outer perimeter and a return path towards the top and bottom regions along the drop surface. The observed time-lapse image of the particle trajectory over many oscillation cycles is shown in Fig. 3a. When the drop shape was strobed precisely at the resonant frequency, the observed tracer particle motion completely lacked the ac component, and appeared as the smooth dc drift. But when the drop shape was strobed slightly off the resonant frequency, the tracer particle showed an ac component of 'pumping-like' action with larger displacement from the prolate to oblate transitions than from the oblate to prolate transitions. We believe this unbalance leads to the observed dc flow. Since the oscillation frequency of the drop (44.4 Hz) was higher than the video recording rate (30 Hz), each frame contained the full oscillatory path for each tracer particles showing up in the video frame as short streaks rather than points. The flow pattern is asymmetrical with respect to the equator of the drop. This pattern is different from the observations made by the previous investigator using pure acoustic levitation approach[4] (Fig. 3b). We think this difference arises from the fact that the prolate shape has a sharper curvature at the upper surface of the drop which creates an asymmetrical velocity profile about the equator. Figure 4 is an instantaneous velocity map of tracers at various points inside the drop during the shape oscillation with respect to the rest coordinate system for Av = 1.29. These data were not corrected for optical distortions caused by the drop curvature; therefore, the values near the boundary of the drop are expected to be less reliable. Because of the optical distortion, the return path of the flow that starts near the equator and ends at the poles of the drop was nearly invisible using just a single side view camera. It was, however, observable from a camera looking down on the drop as the focus was varied through the entire depth of the drop. Figure 5 shows a plot of the flow velocity at the half radius point (y = Ro / 2) vs. the maximum prolate axial ratio Av. Even for an extremely small oscillation amplitude (Av ~ 1.0) a very small dc drift was observable, though the quantitative measurement became more difficult due to the background motion mentioned earlier. Figure 5 indicates, for example, that for a drop oscillating with very small amplitude (Av = 1.030) the flow velocity at y = Ro / 2 is about 1 μm / sec or

3.6mm / hour. Although the drop shape and the flow pattern analyzed in this study were primarily for the case of fundamental mode ($l = 2$) oscillation, it was also possible to excite higher mode as observed previously using the pure acoustic liquid-liquid system[4] and a characteristic internal flow was observable (Fig. 3c).

The flow pattern generated by both the pure acoustic approach[4] and by pure electrostatic approach (this letter) produce similar dc internal flow pattern with only slight difference in the symmetry. This suggests that the dc internal motion within the drop may be intrinsic to the nature of the shape oscillation, and do not reflect any acoustic streaming nor electrostatic effects on the surface of the drop (although these may add to or modify the phenomenon). A potential driving mechanism for this motion is related to the shear force on the surface caused by unequal amount of total air drag between the oblate to prolate transition and the prolate to oblate transition. Another possible mechanism is related to the curvature dependence of pressure. For example, when the drop is at its extreme prolate shape, the poles of the drop having higher curvature would have to be submitted to a higher pressure than the surrounding region. This would initiate a steady flow from higher to lower pressure regions (i.e., from the poles to the equator). Because the time spent over an oscillatory cycle in the prolate shape is longer than in the oblate shape[4], one would expect a net fluid flow from the pole to the equator.

The low-gravity condition of space provides a unique environment for fluid dynamics and macromolecular crystal growth research. Most of these orbiting microgravity research laboratories are not completely immune to vibration-related problems caused by various cooling and circulation fans, treadmills and other moving parts that generate the small to large amplitude vibrations. This implies that any type of fluid related experiment in 1-g or in microgravity is subjected to not only the ac but the dc type of internal flow of varying magnitude depending on the fluid and the environmental characteristics. Observations from previous flight experiments that sometimes, crystals growing from solution migrate very slowly (~50 μm/hour)[7] within the container, indicate the existence of internal flow. This motion was correlated with acceleration disturbances caused by spacecraft jet firings. The result presented here suggests that crystal migration may also be induced by the vibration of the apparatus. Controlled circulation within the solution in the region surrounding the growing protein crystals may enable the researchers to gain the deeper insight into the macromolecular crystal growth process. A drop oscillation technique like that described in this letter may be a good approach to carry out this study, and a containerless fluids research facility such as we described in this letter may be easily adapted to specifically avoid vibrations in 1-g or in space in order to achieve quiescent internal fluid environment.

ACKNOWLEDGMENT

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FIGURE CAPTIONS

FIG. 1. Voltage profile for simultaneous, electrostatic levitation and the shape oscillation of the drop.

FIG. 2. Evolution of the drop shape during an oscillation cycle. Sharper curvature at the top of the prolate shape is due to the higher electric field.

FIG. 3. Time-lapse images of the tracer particle trajectory in the midplane of the oscillating drops over many oscillation cycles for (a) $l = 2$ mode by electrostatic levitation and oscillation method, (b) $l = 2$ mode by previous, acoustic levitation liquid-liquid approach and (c) $l = 4$ mode by electrostatic levitation and oscillation method.

FIG. 4. Instantaneous velocity map of tracers at various points inside the drop (not corrected for optical distortions caused by the drop) during the shape oscillation with respect to the rest coordinate system for maximum prolate ratio L/W of 1.29.

FIG. 5. Flow velocity at the half radius point ($y = R_o / 2$) vs. the maximum prolate axial ratio L/W of the oscillating drop at various amplitudes.

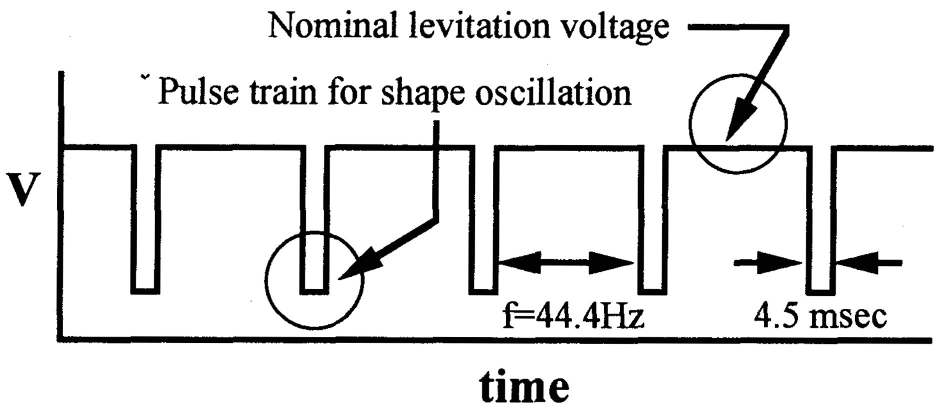

Fig. 1, Sang K. Chung, Physics of Fluids

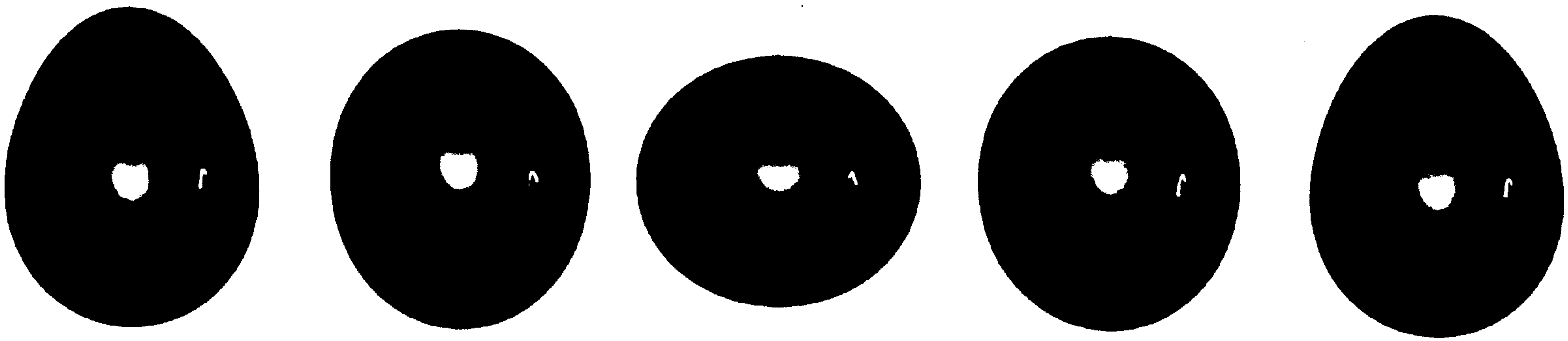

Fig. 2, Sang K. Chung, Physics of Fluids

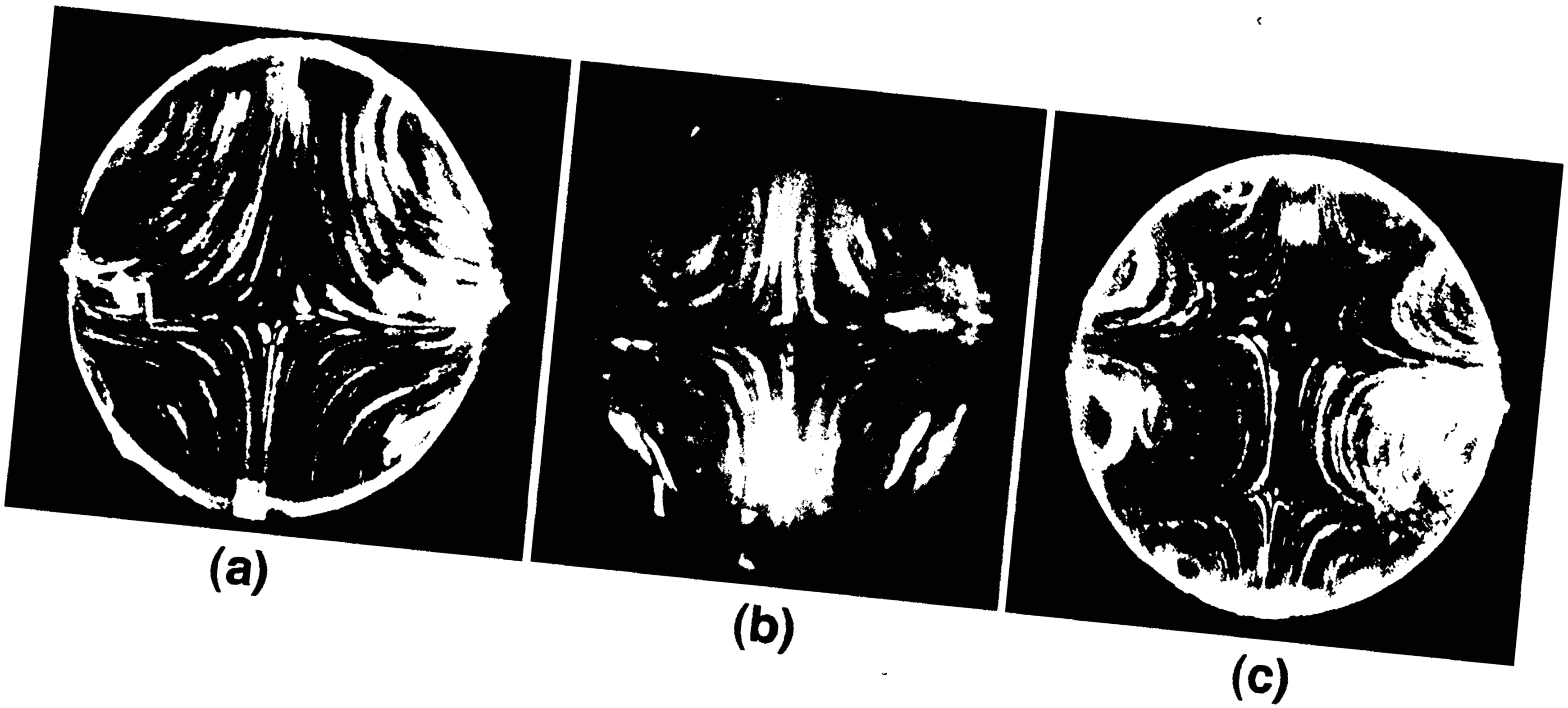

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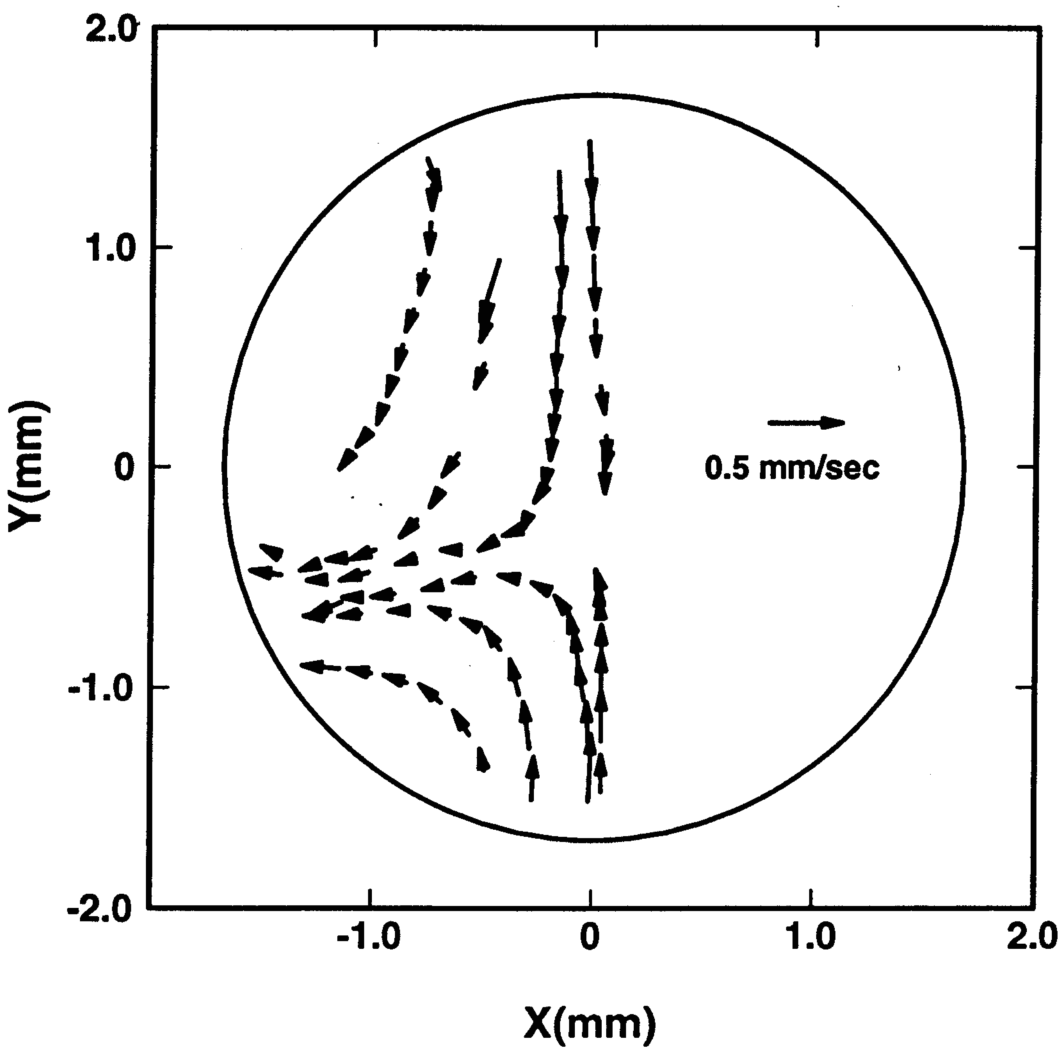
Fig. 4 , Sang K. Chung, Physics of Fluids



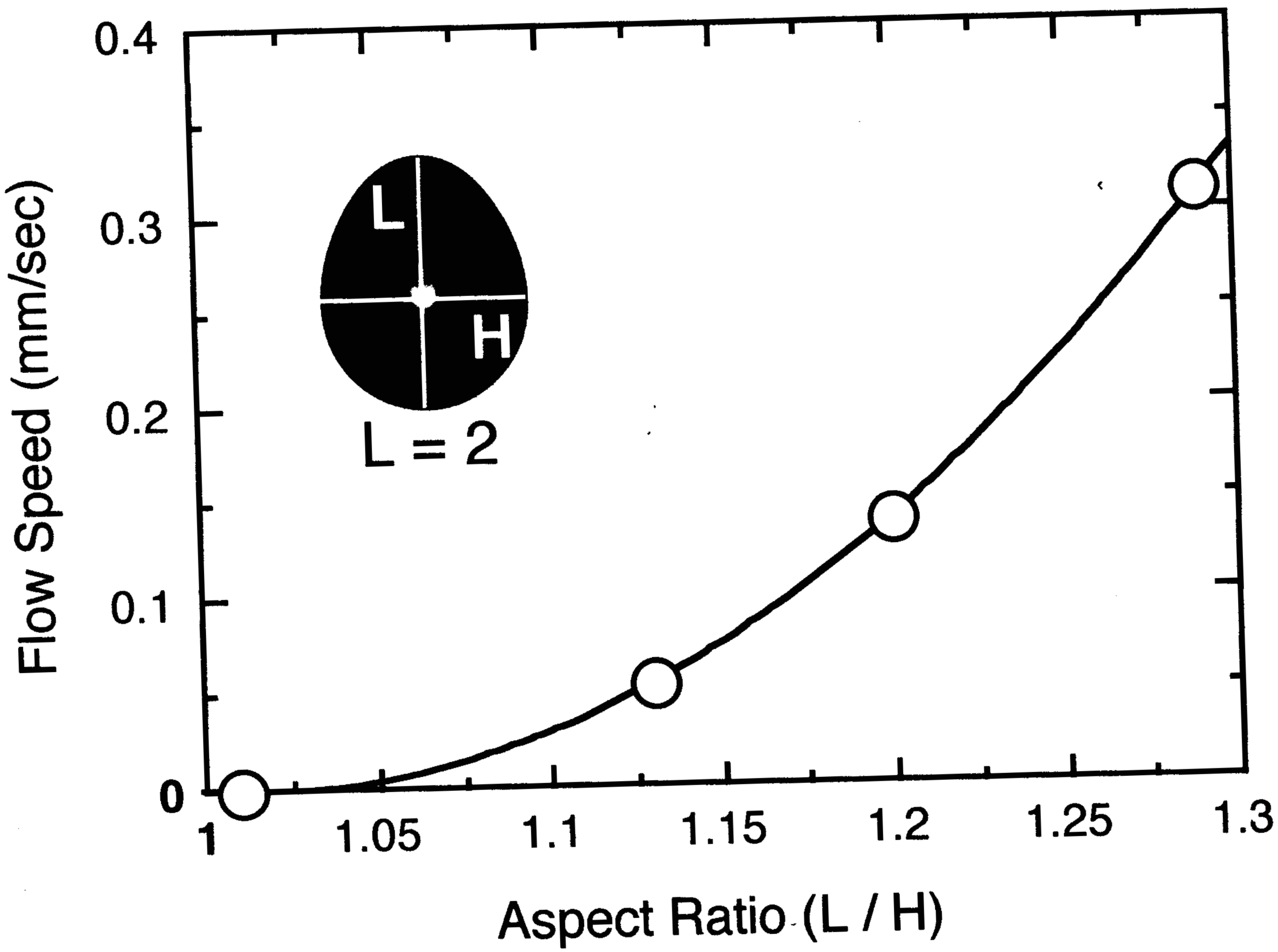


Fig. 5, Sang K. Chung, Physics of Fluids